Effect of a Contaminant Source (CO_2) Inside a Ventilated Room: Thermal Comfort-Air Quality

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Abstract

Numerical results obtained from the analysis of the conjugated heat and mass transfer of an Air-CO_2 mixture inside a ventilated cavity in turbulent flow regime have been presented. Two configurations (case D1 and D2) of the cavity were analyzed, in order to study the thermal behavior and the air quality inside the cavity. A contaminant source (CO2) of 3000 ppm is considered in nine different positions inside the cavity. These positions are identified with the name of CH1, CH2, ... CH9. The air inlet gap is located on the lower side of the vertical wall of the cavity: in the right wall (case D1) and the left wall (case D2). From the results, for the D1 configuration, the lowest value of $T_{average}$ is obtanied in cases where the source of contaminant is located near the heat source (CH3, CH6 and CH9). While for the D2 configuration, the best performance from the standpoint of thermal and air quality corresponds to the cases with a source of contaminant in the positions CH1, CH2 and CH3.

Keywords

Ventilated Room; Thermal Comfort; Air Quality

Nomenclature

$C_{average}$: Average contaminant concentration (CO_2) covering the inside of cavity.

C_{inlet}: Concentration of chemical specie at the mixture inlet, $Kg\text{-}m^{-3}$ o *ppm.*

C_{oulet}: Concentration of chemical specie at the mixture outlet, $Kg\text{-}m^{-3}$ o *ppm.*

C_{source}, C_H: Contaminant source of the chemical specie, $Kg\text{-}m^{-3}$ o *ppm.*

W: Width of the cavity , *m.*

H: Height of the cavity , *m.*

Q: Imposed heat flux on the exterior of opaque wall, $W\ m^{-2}$.

$q_{conv\text{-}ext}$: Convection heat flux towards the exterior of the cavity, $W\ m^{-2}$.

$q_{rad\text{-}ext}$: Radiation heat transfer towards the exterior, $W\ m^{-2}$.

Re: Reynolds number, $\mathrm{Re} = (u_{inlet})(\rho)(H_i)/\mu$.

$T_{average}$: Average temperature of the mixture (Air-CO_2) inside the cavity, ^{o}C *ó* K

T_{inlet}: Temperature of the mixture (Air-CO_2) at the mixture inlet, ^{o}C *ó* K.

T_{oulet}: Temperature of the mixture (Air-CO_2) at the mixture outlet, ^{o}C *ó* K.

u_{inlet}: Horizontal velocity at the mixture inlet, $m\ s^{-1}$.

Greeks Symbols

E: Rate of disipation of k, m^2/s^3

$\overline{\varepsilon}_t$: Overall effectiveness coefficient for temperature distribution

$\overline{\varepsilon}_C$: Overall effectiveness coefficient for contaminant distribution

κ: Turbulence kinetic energy, m^2/s^2.

Introduction

Indoor air pollutants derived from a range of sources are emitted by the fabric of buildings, and may also be a by-product of the activities that are undertaken within them. Sources can be broadly classified as being associated with the activities of building occupants and other biological sources, the combustion of substances for heating or fuel, and emissions from building materials. The concentration of a pollutant indoors depends on the relationship among the volume of air contained in the indoor room, the rate of production or release of the pollutant, the rate of removal of the

pollutant from the air via ventilation, the rate of air exchange with the outside atmosphere, and the outdoor pollutant concentration (Jones). Ventilation is closely related to the comfort level experienced by a person. The comfort is a function of multiple variables such as: air temperature, average radiant temperature, air humidity, air velocity, type of clothing, level of activity, etc. Another purpose of ventilation is to provide a supply of fresh air to the inside spaces in order to dilute contaminants concentration produced by people, equipment and materials. Contaminants dilution is influenced by the amount and quality of exterior air, as well as the way the air is circulated to the interior space (Awbi, Allard). Other useful works related with natural convection in open cavities have been performed by Prakash, Nateghi and Armfield, Singh and Venkateshan and Mohamad. This technical note evaluates the performance of a room with a source of pollutant (CO_2) located within it, in order to obtain thermal comfort and air quality inside room, the traditional way to model ventilated room is thorough cavities with different configurations and conditions. The ventilation parameters used in the evaluation are the overall ventilation effectiveness for temperature distribution and contaminants removal.

Configuration and Mathematical Model

The physical configuration consists of a two-dimension cavity with the air inlet gap on the lower side of the right wall (Case D1) and the left wall (Case D2). For both configurations, the air outlet gap is on the right of the upper wall. The cavity is ventilated through the lower side of the vertical wall with air at temperature Tinlet and a CO2 concentration Cinlet. The vertical right wall is a solid opaque wall subject to a constant heat flux falling normal to the (q) surface. Convective and radiative losses to the outside of the cavity are considered. Finally, the contaminant source (CO2) is considered in nine different positions inside the cavity. These positions are identified with the name of CH1, CH2, ... CH9. The first position (CH1) is in the upper left side of the cavity at a distance of 1 m from the left vertical wall at a height of 2.25 m. The position CH2 is horizontally at a distance of 1 m from the position CH1 with the same height. Position CH3 is at a distance of 1 m from the right vertical wall at the same height of the polluting sources CH1 and CH2. Other contaminant source positions are in that order downwards at a distance of 0.75 m, in equidistant positions, as seen in Figure 1. The nine positions of the source of contaminant have been considered on the configurations D1 and D2. The height and width of the cavity is defined as H and W, respectively. The inlet and outlet gaps height is H_i, the inlet air velocity (u_{inlet}) is a function of the Reynolds number (Re) and the conductive wall thickness is W_m. The governing equations for mixed convection inside a ventilated cavity are mass, momentum, energy and chemical specie (CO_2) conservation equations, averaged in time. These equations systems are not complete due to the presence of the Reynolds stress tensor ($\rho\overline{u_i' u_j'}$) in the momentum equation, the turbulent heat vector ($\rho\overline{u_i' T'}$) in the energy equation and the turbulent mass vector ($\rho\overline{u_i' C'}$) in the chemicals specie. In the Eddy Viscosity Model (EVM), the Reynolds stresses, turbulent heat and mass flux vector are approximated as: $\overline{\rho u_i' u_j'} = -\mu_t\left[\frac{u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right]+\frac{2}{3}\rho\kappa\delta_{ij}$,

$\rho C_p \overline{u_i' T'} = -\frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial x_i}$ and $\rho\overline{u_i' C'} = -\frac{\mu_t}{Sc_t}\frac{\partial C}{\partial x_i}$. Where σ_t is the turbulent Prandtl number and Sc_t is the turbulent Schmidt number. The turbulent viscosity (μ_t) is related to turbulent kinetic energy (κ) and to the turbulent kinetic energy dissipation (ε) by the Kolmorogov-Prandtl empirical expression as: $\mu_t = C_\mu\frac{\rho\kappa^2}{\varepsilon}$. In order to fix the turbulence mathematical problem, the turbulent kinetic energy (κ) and the turbulent kinetic energy dissipation (ε) are used (Henkes et al., [8]). The boundary conditions for the velocity components are on all the solid surfaces and they are zeros, at the air inlet gap, they are $u = u_{inlet}$ and $v_{inlet} = 0$, at the mixture outlet gap $\frac{\partial u}{\partial n} = 0$ and $\frac{\partial v}{\partial n} = 0$, where n is the vector normal to the flow direction. The thermal boundary conditions are at the air inlet gap $T = T_{inlet}$, at the mixture outlet gap $\frac{\partial T}{\partial n} = 0$. On the opaque surface in contact with the fluid inside the cavity, from a thermal balance, $q_{cond-muro} = q_{conv-\text{int}}$, and finally for any other region on the boundary the walls are adiabatic. Boundary conditions for the chemical specie (CO_2) are at the air inlet gap $C = C_{inlet}$, and at the mixture outlet gap we have $\frac{\partial C}{\partial n} = 0$, on the position (CH1, CH2, .CH9) there is a contaminant source that is $C = C_{Source}$ and

for any other region on the boundary walls ,it is taken as $\frac{\partial C}{\partial n}=0$. For the right wall, the governing equation is defined as the heat conduction equation. The boundary conditions for this model are the lower ($y=H_i$) and upper ($y=H$) boundaries are adiabatic; and over the boundary in touch with the environment, a constant heat flux is imposed with convective and radiative losses to the ambient temperature T_{ext} , that is to say, $q=q_{cond-muro}+q_{rad-ext}+q_{conv-ext}$. For the boundary interacting with the cavity, it is assumed that the conductive heat flux through the opaque wall is the same as the convective heat flux to the cavity.

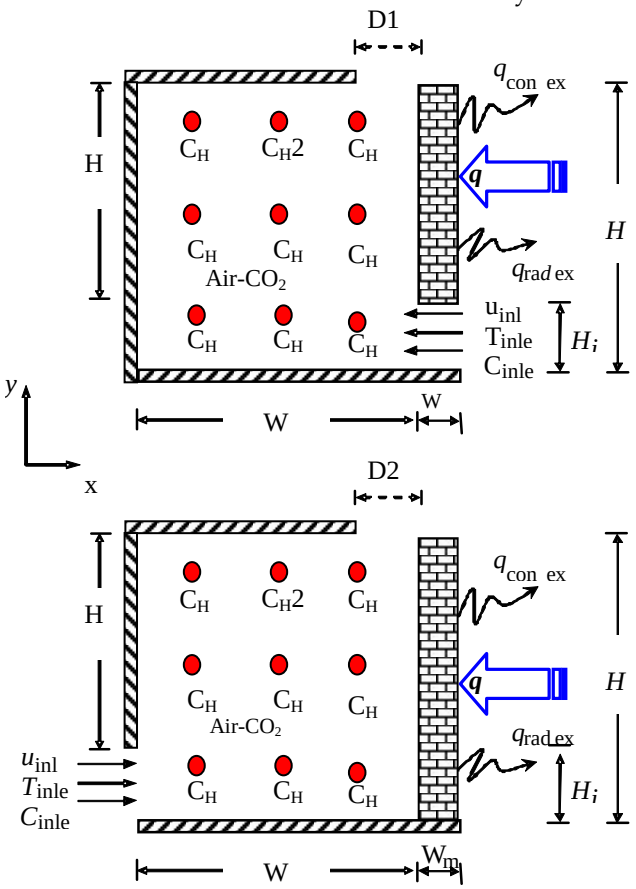

FIG. 1 PHYSICAL MODEL FOR THE VENTILATED CAVITY

Characteristic Parameters

The overall ventilation effectiveness for temperature distribution $\bar{\varepsilon}_t$, provides a quantitative index related to the way in which heat is distributed covering inside the cavity, the higher the value is, the more homogeneous the temperature distribution is. Awbi defined this parameter as $\bar{\varepsilon}_t=\frac{T_{outlet}-T_{inlet}}{T_{average}-T_{inlet}}$. So do the contaminant removal effectiveness $\bar{\varepsilon}_C$ which provides a quantitative index related to the way in which pollutants are distributed covering inside the cavity, the higher the value of $\bar{\varepsilon}_C$ is, the more homogeneous the pollutants distribution is. This parameter is defined as $\bar{\varepsilon}_C=\frac{C_{outlet}-C_{inlet}}{C_{average}-C_{inlet}}$.

Numerical Procedure

The governing equations describing the flow, heat and mass transfer were discretized by the finite volume technique (Patankar, [9]). Coupling among the mass and momentum conservation equations has been carried out using the SIMPLEC algorithm defined by (Van Doormal and Raithby, [10]). Convective terms were approached by the hybrid scheme and diffusive terms by the centered scheme. The algebraic equations system is solved through the line by line method (LBL) with alternating direction implicit scheme (ADI). If the values in the mass balance for every control volume as well as the residual values of the different equations are significantly low, then the overall convergence will be achieved (typically 10^{-8}). The accuracy of the numerical results is verified through numerous tests based on the grid size effect. A mesh independence study has been carried out with numerical meshes varying from 71x61 to 121x111 with 10 nodes increments on each axis. The discretization for the opaque wall is always 10 nodes on the horizontal direction for all the meshes. A maximum deviation of 1.0 % for the variables between meshes 111x101 and 121x111 has been observed. Therefore, a 111x101 grid was used for all cases considered herein. The results of this validation were presented by Serrano [11], with satisfactory results. From the comparison of results, our numerical code in consideration is sufficiently tested. The Reynolds stresses that turbulent heat and mass flux vector are approximated as :-

$$\overline{\rho u_i' u_j'}=-\mu_t\left[\frac{u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right]+\frac{2}{3}\rho\kappa\delta_{ij} \quad (1)$$

$$\rho C_p\ \overline{u_i' T'}=-\frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial x_i} \quad (2)$$

$$\rho\ \overline{u_i' C'}=-\frac{\mu_t}{Sc_t}\frac{\partial C}{\partial x_i} \quad (3)$$

Results and Discussions

For this study, an actual size room cavity 4.0 x 3.0 m² (*H* x *W*) has been considered. The inlet and outlet of

the mixture air-CO_2 are H_i=0.3 m height, the same size as the air conditioning diffusers. The material for the opaque wall is construction common brick with the thickness W_m=12 cm . Supplied air temperature has been set to be 24°C and C_{inlet} =340 ppm and the outside conditions for the opaque wall are a convection heat transfer coefficient (h_{ext}) of 6.8 W/m² K, which corresponds to a wind velocity of 3 m/s and ambient temperature of 35°C. The heat flux on this wall had a constant value of 750 W/m² (ASHRAE, 2005 [12]). The Reynolds number is considered for values 10000 and 20000. The CO_2 contaminant source considered is 3000 ppm (maximun values for a room environment).

Table 1 shows the summary of results for each of the locations of the contaminant source (CH1, CH2, CH9 ...) for the D1 configuration with *Re* = 10000. The average temperature and concentration of CO_2 in the cavity is shown. Similarly, it shows the temperature distribution efficiency (ε_t) and the contaminant removal effectiveness (ε_c) inside the cavity. It is observed that average temperature values are in the range of 24.3 to 24.5°C, corresponding to the position of the source of contaminant in CH2, CH3, CH6 and CH9, for these positions, and larger values of ε_t can be achieved. In addition, the lowest value of temperature (24.3°C) has been obtained for the location CH3, with the corresponding value ε_t = 77.8%. In general, it can be said that from the thermal point of view, the best results are obtained for the positions of the contaminant source closest to the outflow opening. The average concentration is the lowest when the pollution source is located in the top positions: CH1, CH2 and CH3 (from 382 to 391 ppm). For these positions, too, belongs to the highest values of ε_c (from 40.5 to 58.3%). These results indicate that removal of contaminant should be at the top, the closest to the position of the source of contaminant. Further, it can be seen that the locations CH7, CH8 and CH9, corresponding to the position of the source in lower part of the cavity, have the lowest values of ε_c ($13.1 \le \varepsilon_c \le 13.4$).

Analogously, Table 2 shows the summary of results for each of the locations of the contaminant source (CH1, CH2, CH9 ...) for the D1 configuration with *Re* = 20000. It is observed that the lowest value of temperature (24.2°C) has been obtained for the location CH9, with the corresponding value ε_t = 52.6%. This ε_t result shows that when the Reynolds number is increased, the temperature homogeneity decreases within the cavity. The average concentration is the lowest when the pollution source is located in the top positions: CH1, CH2 and CH3 (from 403 to 418 ppm). For these positions, too, belongs to the highest values of ε_c (from 34.6 to 38.1%). These results indicate that removal of contaminant should be at the top, the closest to the position of the source of contaminant. It is observed as well that, this ε_c result shows that when the Reynolds number is increased, the CO_2-Concentration homogeneity declines within the cavity.

TABLE 1 RESULTS FOR D1 CONFIGURATION FOR RE = 10000.

Re=10000				
C_{Source} POSITION	$T_{average}$ (ºC)	$C_{average}$ (ppm)	ε_t	ε_c
CH1	24.7	382	38.8	58.3
CH2	24.5	390	47.8	52.3
CH3	24.3	391	77.8	40.5
CH4	25.2	435	21.0	22.8
CH5	24.9	460	26.9	21.5
CH6	24.5	440	49.5	21.4
CH7	25.0	463	24.0	13.4
CH8	25.0	493	25.1	13.6
CH9	24.4	470	57.0	13.1

TABLE 2 RESULTS FOR D1 CONFIGURATION FOR *RE* = 20000.

Re=20000				
C_{Source} POSITION	$T_{average}$ (ºC)	$C_{average}$ (ppm)	ε_t	ε_c
CH1	24.8	403	25.4	34.6
CH2	24.7	418	32.7	37.5
CH3	24.5	405	39.1	38.1
CH4	24.9	477	22.3	17.2
CH5	24.6	469	32.5	18.2
CH6	24.2	421	71.5	20.8
CH7	25.0	463	21.0	13.7
CH8	24.5	483	38.6	13.5
CH9	24.2	448	52.6	16.1

Table 3 shows the summary of results for each of the locations of the contaminant source (CH1, CH2, CH9 ...) for the D1 configuration with a Reynolds number of 10000 and 20000. The same ventilation parameters of Table 1 and 2 are presented in this table. For *Re*=10000, it is observed that the values of lower average temperature are obtained for three locations: CH1, CH2 and CH3 corresponding to the cases where the pollution source is located at the top of the cavity (≈

24.1 to 24.2° C). Of these three positions to the pollution source, CH1 position has the best distribution of temperature (30.5%). The average concentration is the lowest when the pollution source is located in the top positions: CH1, CH2 and CH3 (from 384 to 419 ppm). For these positions, too, belongs to the highest values of ε_c (from 49.1 to 54.9%). The better distribution of pollutant corresponds to the location CH3. Additionally, it can be seen that the locations CH7, CH8 and CH9 which correspond to the position of the source in lower part of the cavity, have the lowest values of ε_c ($12.8 \leq \varepsilon_c \leq 13.9$). For a value of Re = 20000, similar to the results of Re = 10000, the best results for ventilation correspond to positions CH1, CH2 and CH3. This comparison shows that increasing the value of Reynolds number allows an increase in the values of ε_t and ε_c, from which it is concluded for this configuration that the homogeneity of temperature and concentration of CO_2 have been improved.

TABLE 3 RESULTS FOR D2 CONFIGURATION FOR RE = 10000 AND *RE* = 20000.

C_{Source} POSITION	$T_{average}$ (ºC)	$C_{average}$ (ppm)	ε_t	ε_c
Re=10000				
CH1	24.1	384	30.5	49.1
CH2	24.2	395	24.2	50.6
CH3	24.2	419	22.3	54.9
CH4	24.8	446	5.6	22.6
CH5	24.7	456	6.1	21.5
CH6	24.5	444	8.3	20.9
CH7	25.2	504	3.4	13.9
CH8	25.2	515	3.6	13.6
CH9	24.7	491	6.3	12.8
Re=20000				
CH1	24.1	396	59.3	73.1
CH2	24.1	404	62.2	73.0
CH3	24.1	391	50.0	73.7
CH4	24.3	405	10.5	58.2
CH5	24.4	441	9.8	61.2
CH6	24.3	465	11.7	51.4
CH7	25.0	429	4.0	50.9
CH8	25.0	438	3.6	44.8
CH9	24.5	435	7.4	37.4

Conclusion

Based on the results of the heat and mass transfer in a ventilated cavity, it is concluded that

- D1 configuration: in cases where the source of contaminant is located near the heat source (CH3, CH6 and CH9), the lowest value of $T_{average}$ with respect to other positions of CO_2 source can be obtained.
- D2 configuration: for cases with a source of contaminant in the positions CH1, CH2 and CH3 (top) the best performance can be achieved from the standpoint of thermal and air quality.
- From an air quality point of view, the Standard ASHRAE 62-2007 [13] states that the maximum concentration of carbon dioxide (CO_2) inside a room environment is 700 ppm, in order to be acceptable for air quality purposes. In general, the configurations D1 and D2 fulfill this requirement.

In general, the air inflow is either near or far from the heat source and/or source of the pollutant, and the optimum location to situate the outlet flow of the mixture air-CO_2 is close to the heat source.

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